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KAON RARE DECAYS

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ABSTRACT

Recent results and future prospects in the rare kaon-decay experiments at KEK, BNL, CERN and FNAL are reviewed. Emphasis is placed on the quark flavor dynamics in the flavor-changing neutral current processes. Experimental and data-analysis techniques developed in the rare decay experiments are discussed.

1 Introduction

The history of rare kaon-decay physics began in 1964 with the unexpected evidence for the CP violating $K_L^0 \to \pi^+\pi^-$ decay [1] at the sensitivity of 10^{-3}. This discovery, which in later stimulated Kobayashi and Maskawa [2] to introduce the third generation of quarks and leptons, was one of the major contributions of kaon physics toward establishing the Standard Model (SM). Another famous

contribution was the absence of kaon decays due to flavor-changing neutral current (FCNC), $K_L^0 \to \mu^+\mu^-$, $K^+ \to \pi^+ e^+ e^-$ and $K^+ \to \pi^+ \nu\bar{\nu}$, in 1960's. The GIM mechanism [3] explained it with the unitary matrix for weak-eigenstate mixing. All of these had been achieved in advance of the charm-quark discovery in 1974.

The next theoretical milestone emphasized here was so-called "Inami-Lim loop functions" [4] in 1981 for FCNC processes with heavy quarks and leptons. In addition to the continual searches for decays at higher level than the SM predictions, the anticipation of detecting rare kaon decays in the SM range got more and more realistic with the rise of the top-quark mass. The first evidence for the $K^+ \to \pi^+ \nu\bar{\nu}$ decay reported by the E787 collaboration [5] in 1997 opened a new era of "testing the SM by measuring rare processes". In the current experiments (tab.1), with millions of kaon decays per second by high-intensity proton synchrotrons, searches and measurements with the sensitivity of $10^{-7} \sim 10^{-12}$ are being performed; these are the frontiers that no other heavy-flavor physics can reach at present.

Table 1: *Rare kaon-decay experiments being reviewed in this article. "$\surd$" means data taking of the experiment is completed. "$*$" means detector construction of the experiment is not started.*

lab	accelerator		experiment	kaon decay
KEK	PS	(12 GeV)	E246 $\surd$	stopped K^+
			E391a	K_L^0
BNL	AGS	(25 GeV)	E787 $\surd$ / E949	stopped K^+
			E865 $\surd$	in-flight K^+
			E871 $\surd$	K_L^0
			KOPIO *	K_L^0
CERN	SPS	(450 GeV)	NA48	K_L^0, K_S^0
FNAL	Tevatron	(800 GeV)	KTEV $\surd$	K_L^0
	Main Injector	(120 GeV)	CKM *	in-flight K^+

In this article, recent results and future prospects in the rare kaon-decay experiments are briefly reviewed. "ϵ'/ϵ" CP violation in kaon decays is reviewed by E. Cheu [6]. For further and latest information on the field, in particular on the radiative decays and chiral dynamics which are not covered here, the article by A.R. Barker and S.H. Kettell [7] and the Web site of the KAON2001

conference [8] are recommended.

Remind that the experimental upper limits in this article are at 90% confidence level.

2 FCNC

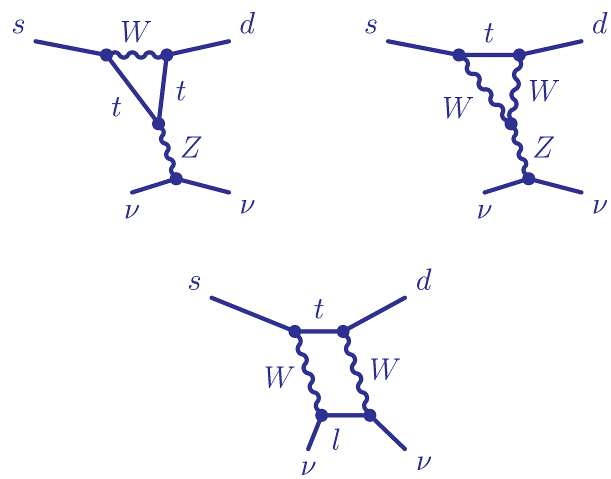

Figure 1: *Penguin and Box diagrams in $K \to \pi\nu\bar{\nu}$.*

The FCNC process in kaon decays is strange-quark to down-quark transition and is induced in the SM by the W and Z loop effects as Penguin and Box diagrams (fig.1). The top-quark in the loops dominates the transition because of its heavy mass, and the quantity λ_t:

$$\lambda_t \equiv V_{ts}^* \cdot V_{td} = A^2\lambda^5 \cdot (1 - \rho - i\eta), \tag{1}$$

where A, λ, ρ and η are the Wolfenstein parameterization of the Cabibbo-Kobayashi-Maskawa(CKM) matrix, is measured. The decays are rare due to λ^5, and are precious because the important parameters ρ and η can be determined from them. The decay amplitude of K_L^0 is a superposition of the amplitudes of K^0 and $\bar{K}^0$ and is proportional to the imaginary part of V_{td} (and to η); observation of rare K_L^0 decays, in particular the $K_L^0 \to \pi^0\nu\bar{\nu}$ decay, is a new evidence for direct CP violation.

Theoretical calculations are simple if the kaon decay accompanies neutrinos [1]. For charged leptons in the final state, the transition is also induced by long-distance effects with γ emission due to hadronic interactions. Rare kaon decays with charged leptons are easier to detect in experiments but have difficulties in theoretical interpretation. For example, a precise measurement of the branching ratio of the $K_L^0 \to \mu^+\mu^-$ decay $(7.18 \pm 0.17) \times 10^{-9}$ was achieved by the E871 collaboration [9] based on the 6.2K signal events. However, the decay mode is saturated by an absorptive process: $K_L^0 \to \gamma\gamma$ and the two γ's subsequently scattered into muons. The estimated branching ratio due to this process, called "unitarity bound" [10], is $(7.07 \pm 0.18) \times 10^{-9}$. In this decay mode we basically look at a QED process and cannot get good information on the CKM matrix elements.

An idea is to use K_S^0 decays; when a CP violating effect is observed in K_L^0, the effect can be cross-checked by a null result in the corresponding K_S^0 decay. An example is a large CP-violating asymmetry $(13.6 \pm 2.5_{stat} \pm 1.2_{syst})\%$ observed by the KTEV collaboration [11] in the distribution of $K_L^0 \to \pi^+\pi^-e^+e^-$ decays, whose branching ratio was $(3.2 \pm 0.6_{stat} \pm 0.4_{syst}) \times 10^{-7}$, in the angle between the decay planes of the e^+e^- and $\pi^+\pi^-$ pairs in the K_L^0 rest frame. The asymmetry was confirmed by a preliminary result from the NA48 collaboration [12], $(13.9 \pm 2.7_{stat} \pm 2.0_{syst})\%$. NA48 also measured the asymmetry in the distribution of $K_S^0 \to \pi^+\pi^-e^+e^-$ decays, whose branching ratio was $(4.3 \pm 0.2_{stat} \pm 0.3_{syst}) \times 10^{-5}$, with the same detector. No asymmetry $(-0.2 \pm 3.4_{stat} \pm 1.4_{syst})\%$ was observed, which indicates that the large asymmetry in K_L^0 is not an effect due to final-state interactions nor an artifact due to acceptance errors in the measurement.

3 $K_L^0 \to \pi^0 e^+e^-$

An upper limit on the branching ratio of the $K_L^0 \to \pi^0e^+e^-$ decay $< 5.1 \times 10^{-10}$ was set by the KTEV collaboration [13] with their 1997 data set [2] based on two events in the signal region with the background estimate of 1.06 ± 0.41 events (fig.2). The limiting background was the radiative Dalitz decay $K_L^0 \to e^+e^-\gamma\gamma$, whose branching ratio was $(6.9 \pm 1.0) \times 10^{-7}$ [14], when $m_{\gamma\gamma}$ was equal to

[1] Long-distance contributions are negligible, and the hadronic matrix element is extracted from the $K \to \pi e\nu$ decay.

[2] KTEV has the 1999 data set, which is being analyzed.

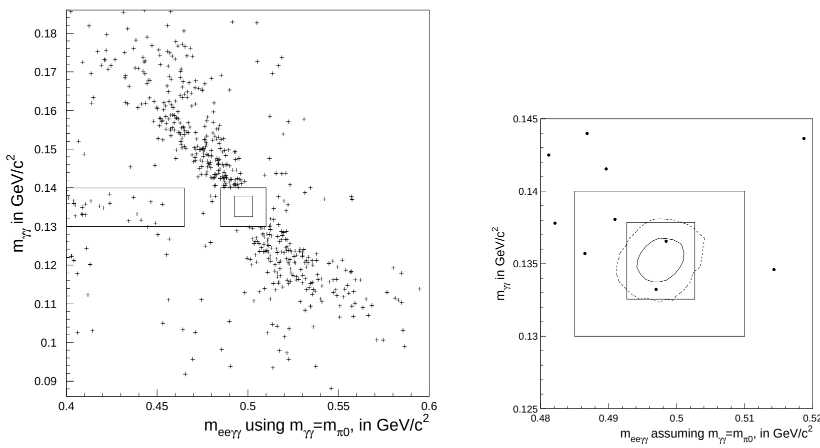

Figure 2: *KTEV result on* $K_L^0 \to \pi^0 e^+ e^-$*: the distribution of reconstructed two photon mass* $m_{\gamma\gamma}$ *vs reconstructed mass of the four particle system* $m_{ee\gamma\gamma}$ *(left) and the same distribution on an expanded scale around the signal region after phase space fiducial cuts were imposed (right).*

the π^0 mass. In the analysis, the "blind" region ($m_{\gamma\gamma} = 135 \pm 5$ MeV/c^2, $485 < M_{ee\gamma\gamma} < 510$ MeV/c^2) and the signal region ($m_{\gamma\gamma} = 135.20 \pm 2.65$ MeV/c^2, $m_{ee\gamma\gamma} = 497.67.20 \pm 5.00$ MeV/c^2) were blanked out until the analysis procedure and selection criteria ("cuts") were finalized.

There are three contributions to the $K_L^0 \to \pi^0 e^+ e^-$ decay: a direct CP-violating contribution, a CP conserving contribution through $\pi^0\gamma^*\gamma^*$ intermediate states and an indirectly CP-violating contribution due to the K_1 component of K_L^0. The first contribution was predicted to be $(4.3 \pm 2.1) \times 10^{-12}$ [15] in the SM and the second contribution was estimated to be around 5×10^{-12} [16] from measurements of the $K_L^0 \to \pi^0\gamma\gamma$ decay [17] [12]. The CP conserving $K_S^0 \to \pi^0 e^+ e^-$ decay helps to do reliable estimation of the third contribution [3]. An upper limit on the branching ratio of the $K_S^0 \to \pi^0 e^+ e^-$ decay $< 1.4 \times 10^{-7}$ was obtained by the NA48 collaboration [18], using data col-

[3] The branching ratio for K_L^0 is 0.3% of the branching ratio for K_S^0 because of $|\epsilon|^2$ and the ratio of their lifetimes.

lected in 1999 during a 40-hour run with a high-intensity K_S^0 beam, based on zero events in the signal region with the background estimate of < 0.15 events (fig.3). In the SM the branching ratio of the $K_S^0 \to \pi^0 e^+ e^-$ decay is predicted to be $10^{-9} \sim 10^{-8}$ [19]. NA48 is going to take K_S data in 2002 with higher intensity and new target station, and get $\times 50$ improvement on the decay mode.

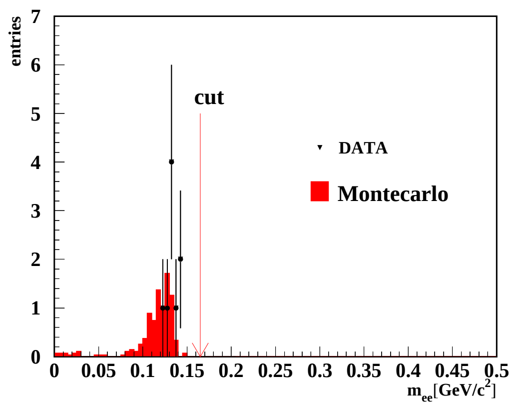

Figure 3: *NA48 result on $K_S^0 \to \pi^0 e^+ e^-$: reconstructed invariant mass distribution of the e^+e^- pair selected as $K_S^0 \to \pi^0 e^+ e^-$. The cut was imposed to remove the background from the $\pi^0 \to e^+ e^- \gamma$ decay.*

4 $K^+ \to \pi^+ \nu\bar{\nu}$

The branching ratio of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay is represented in the SM as:

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = 4.11 \times 10^{-11} \times A^4 \times X(x_t)^2 \times [\ (\rho_0 - \rho)^2 \ + \ \eta^2\ ] \qquad (2)$$

where $X(x_t)$ is the Inami-Lim loop function with the QCD correction, $x_t \equiv m_t^2/m_W^2$ and ρ_0 is estimated to be $1.4 \sim 1.6$ [4]. The theoretical uncertainty is 7% from the charm-quark contribution in the next-to-leading-logarithmic QCD calculations [20]. With the ρ-η constraints from other kaon and B-meson

[4] $\rho_0 - 1$, without which the branching ratio should be proportional to $|V_{td}|^2$, is due to the charm-quark contribution.

decay experiments, the SM prediction of the branching ratio is $(0.75 \pm 0.29) \times 10^{-10}$ [15]. Using only the results on $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing, a branching ratio limit $< 1.15 \times 10^{-10}$ can be extracted [21]. New physics beyond the SM could affect the branching ratio [22]. In addition, the two-body decay $K^+ \rightarrow \pi^+ X^0$, where the X^0 is a weakly-interacting light particle such as a familon [23], could also be observed as a "π^+ plus nothing" decay with a monochromatic pion. Since the effects of new physics are not expected to be too large, a precise measurement of a decay at the level of 10^{-10} is required.

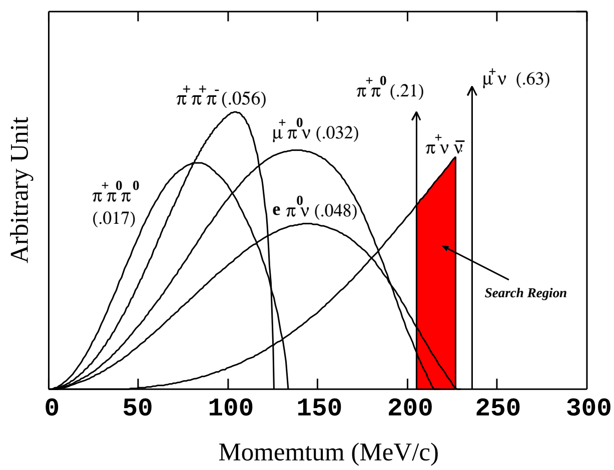

Figure 4: *Momentum spectrum of the charged particles from K^+ decays at rest.*

The E787 and E949 collaborations for a study of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and related decays measure the charged track emanating from K^+ decays at rest. The π^+ momentum from $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is less than 227MeV/c, while the major background sources of $K^+ \rightarrow \pi^+\pi^0$ ($K_{\pi 2}$, 21.2%) and $K^+ \rightarrow \mu^+\nu$ ($K_{\mu 2}$, 63.5%) are two-body decays and have monochromatic momentum of 205MeV/c and 236MeV/c, respectively (fig.4). The region "above the $K_{\pi 2}$" between 211MeV/c and 229MeV/c is adopted for the search. Background rejection is essential in this experiment, and the weapons for redundant kinematics measurement, μ^+ rejection, and extra-particle and photon veto are employed. Each weapon should have a rejection of $10^5 \sim 10^6$, and reliable estimation of these rejections using real data is the key of the experiment.

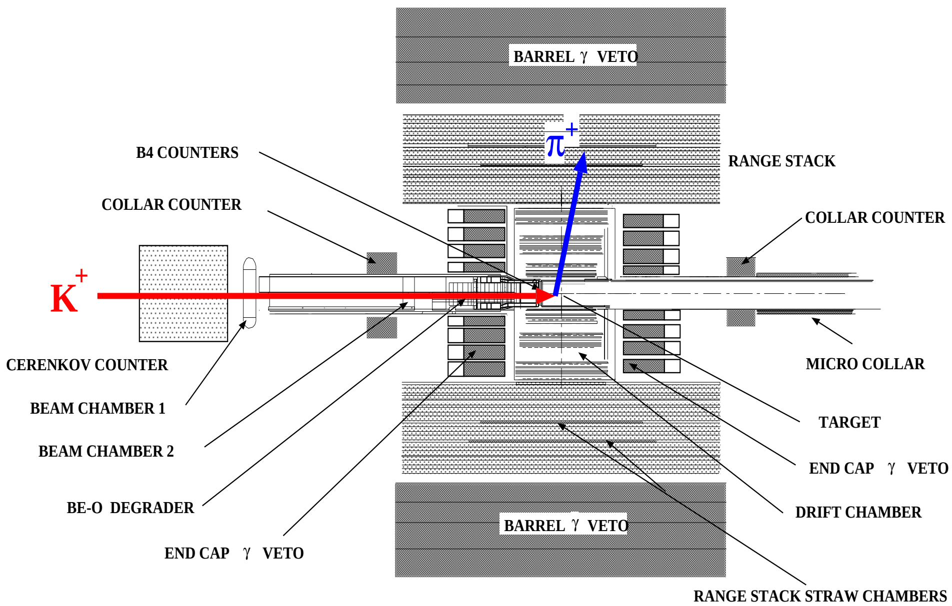

Figure 5: *Schematic side-view of the E787/E949 detector at BNL.*

The E787/E949 detector (fig.5) is a solenoidal spectrometer with the 1.0-Tesla field directed along the beam line. Slowed by a BeO degrader, kaons of about 700MeV/c from AGS reach the scintillating-fiber target at the center of the detector and decay at rest. A delayed coincidence requirement ($>$ 2nsec) of the timing between the stopping kaon and the outgoing pion helps to reject backgrounds of pions scattered into the detector or kaons decaying in flight. Charged decay products pass through the drift chamber, lose energy by ionization loss and come to rest in the Range Stack made of plastic scintillators and straw chambers. Momentum, kinetic energy and range are measured to reject the backgrounds by kinematic requirements. For further rejection of μ^+ tracks from $K_{\mu 2}$ the decay chain $\pi^+ \to \mu^+ \to e^+$ is identified in the Range Stack counter in which the π^+ comes to rest, using output pulse-shape information of the counter. $K_{\pi 2}$ and other decay modes with extra particles (photon, e, ...) are vetoed by the in-time signals in the hermetic shower counters.

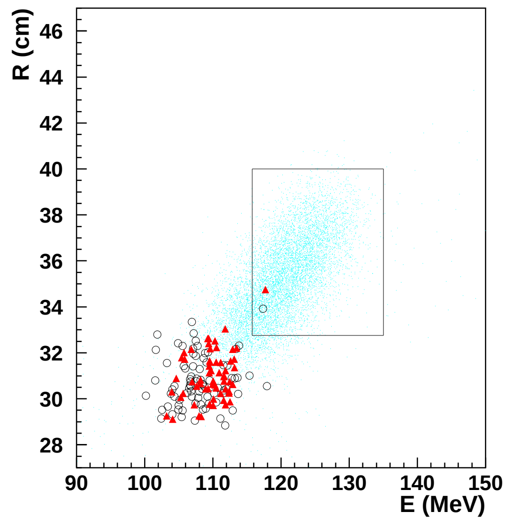

Figure 6: *E787 result on $K^+ \to \pi^+ \nu \bar{\nu}$: range vs kinetic energy plot of the final sample. The circles are for the 1998 data and the triangles are for the 1995-1997 data set. The simulated distribution of expected events from $K^+ \to \pi^+ \nu \bar{\nu}$ is indicated by dots. The box indicates the signal acceptance region.*

Final results from E787 were announced [24] about five months after the XXI Physics in Collision conference was held, including a new 1998 data set of comparable sensitivity to the 1995-1997 data set already reported [25]. One new event was observed in the new data set, bringing the total for the combined data set to two (fig.6). Including all data taken, the backgrounds were estimated to contribute 0.15 ± 0.05 events. The branching ratio of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay was $1.57^{+1.75}_{-0.82} \times 10^{-10}$. A constraint $2.9 \times 10^{-4} < |\lambda_t| < 1.2 \times 10^{-3}$ was provided without reference to the B-meson system.

The E949 experiment [26] continues the study at the AGS based on the experience of E787. E949 is expected to reach a sensitivity of $(8-14) \times 10^{-12}$ in $\sim$2 years of running and determine $|\lambda_t|$ to $20-30\%$. Detector upgrade (additional shower counters in the barrel and beam regions to improve photon detection, new beam counters, new trigger system, Range Stack readout by TDC for deadtime reduction, ...) is completed, and the physics run starts in 2001.

5 $K_L^0 \to \pi^0 \nu \bar{\nu}$

The branching ratio of the neutral counterpart, the $K_L^0 \to \pi^0 \nu \bar{\nu}$ decay, is represented in the SM as:

$$B(K_L^0 \to \pi^0 \nu \bar{\nu}) = 1.80 \times 10^{-10} \times A^4 \times X(x_t)^2 \times \eta^2 \tag{3}$$

and the SM prediction is $(2.6 \pm 1.2) \times 10^{-11}$ [15]. A model-independent bound [27]

$$B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 4.4 \times B(K^+ \to \pi^+ \nu \bar{\nu}) < 2.6 \times 10^{-9} \tag{4}$$

can be extracted from its isospin-relation to the $K^+ \to \pi^+ \nu \bar{\nu}$ decay.

In comparison with the K^+ case, $K_L^0 \to \pi^0 \nu \bar{\nu}$ has some advantages.

- The theoretical uncertainty, $\sim$1%, is smaller.
- No $K_{\mu 2}(K_L^0 \to \mu^+ \mu^-)$ background has to be worry about.
- $K_{\pi 2}(K_L^0 \to \pi^0 \pi^0)$ has been suppressed to 10^{-3}.

However, the following severe difficulties exists.

- The signal is an in-flight K_L^0 decay into "π^0 plus nothing" in a neutral beam line with plenty amount of π^0's coming from K_L^0 decays and neutrons, which could easily create π^0's with residual gas.
- No kinematic constraint (initial kaon, decay vertex, ...) is available with the usual techniques for neutral kaon experiments.
- The expected branching ratio is low enough.

To beat the major background from $K_L^0 \to \pi^0 \pi^0$ in case two out of four photons are missed, photon detection with quite-low inefficiency ($< 10^{-3} \sim 10^{-4}$) is required to the detector.

The current best upper limit on the branching ratio of the $K_L^0 \to \pi^0 \nu \bar{\nu}$ decay $< 5.9 \times 10^{-7}$ was set by the KTEV collaboration [28] with their 1997 data set based on zero events in the signal region with the background estimate of $0.12^{+0.05}_{-0.04}$ events (fig.7). The Dalitz decay mode $\pi^0 \to e^+ e^- \gamma$ (1.2%) for the final state of $K_L^0 \to \pi^0 \nu \bar{\nu}$ was used in this search. However, to reach the SM sensitivity, reconstructing $\pi^0 \to \gamma\gamma$ from the $K_L^0 \to \pi^0 \nu \bar{\nu}$ has to be considered. A search for $K_L^0 \to \pi^0 \nu \bar{\nu}$ with $\pi^0 \to \gamma\gamma$ was performed by the

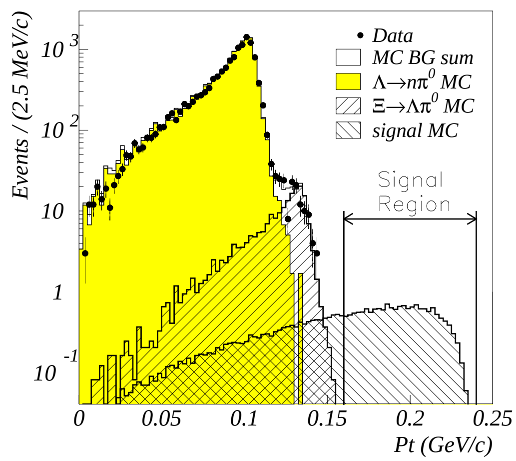

Figure 7: *KTEV result on $K_L^0 \to \pi^0\nu\bar{\nu}$: the distribution of total momentum transverse to the K_L^0 flight direction.*

KTEV collaboration [29)] with their one-day special run; an upper limit on the branching ratio was determined to be $< 1.6 \times 10^{-6}$ based on one event in the signal region with the background estimate of 3.5 ± 0.9 events.

6 Future prospects in $K \to \pi\nu\bar{\nu}$ experiments

Measurement of $B(K_L^0 \to \pi^0\nu\bar{\nu})$ and $B(K^+ \to \pi^+\nu\bar{\nu})$ is the issue of kaon physics in the next five to ten years. In the ρ-η plane, the height of the "unitarity triangle" is proportional to $B(K_L^0 \to \pi^0\nu\bar{\nu})^{1/2}$ and a side of it is to $B(K^+ \to \pi^+\nu\bar{\nu})^{1/2}$. The area of the triangle is proportional to so-called "Jarlskog invariant" [30)] in kaon sector:

$$J_{CP} = Im(V_{ts}^* \cdot V_{td} \cdot V_{us} \cdot V_{ud}^*) = \lambda(1 - \frac{\lambda^2}{2}) \times Im(\lambda_t) \quad (5)$$

and is directly related to these decay modes [5]. If both branching ratios are measured with ~10% precision (~100 signal events) with highly sophisticated and special-purpose detectors, the triangle is determined with good precision

[5] A constraint on $|\lambda_t|$ from $K^+ \to \pi^+\nu\bar{\nu}$ sets an upper limit on $Im(\lambda_t)$.

only from the information in kaon sector. Comparing with the triangle by B-meson system, it can be tested whether the source of CP violation is only from the CKM phase or not.

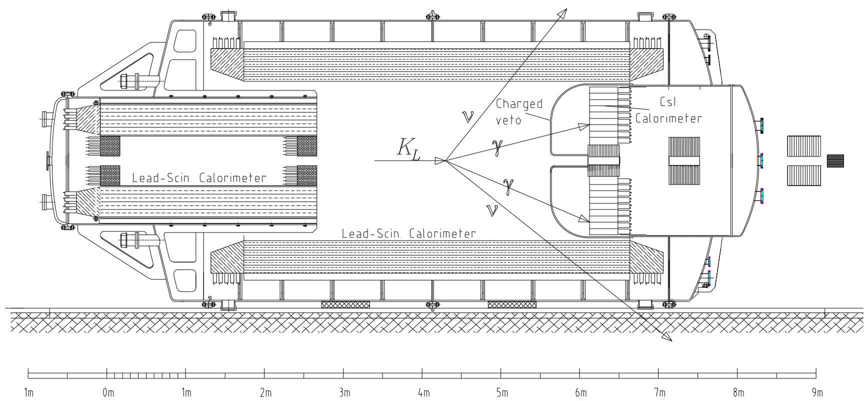

Figure 8: *Side-view of the E391a detector at KEK under construction.*

The E391a experiment [31)] (fig.8) is the first dedicated search for the $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay. A collimated "pencil" neutral beam is designed carefully. A calorimeter with CsI crystals detects two photons from π^0 and measures their energy and position. The K_L^0-decay vertex position along the beam line is determined from the constraint of π^0 mass. Calorimeters which cover the decay region intend to do hermetic photon veto and reject the background from $K_L^0 \to \pi^0\pi^0$. Beam line survey and detector construction were started, and the data taking is scheduled from 2003. The goal of E391a is to reach a sensitivity at 10^{-10}, and they plan to continue the study at the new 50GeV proton synchrotron in the High Intensity Proton Accelerator Facility [32)], which started construction in Japan this year.

More ambitious proposal is the KOPIO experiment [33)] (fig.9), whose principles are to give kinematic constraints to the K_L decay as much as possible. A RF-bunched proton beam from AGS makes low-energy K_L^0's (around 800MeV/c) with a large targeting angle, so that the momentum of each kaon

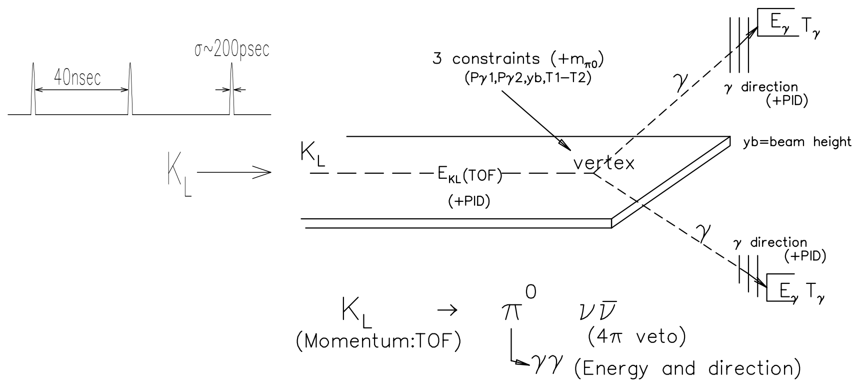

Figure 9: *Principles of the proposed KOPIO detector at BNL.*

is measured with TOF technique and the decay can be analyzed in the K_L^0 rest frame. A combination of the pre-radiator and Shashlik calorimeter intends to measure the timing, energy, position and angle of low energy photons and fully reconstruct the decay. The goal of KOPIO is to observe 50 signal events in the SM with a signal-to-background ratio of 2.

For $K^+ \rightarrow \pi^+\nu\bar{\nu}$, the CKM experiment [34)] (fig.10) intends to study the decay mode with in-flight K^+ decays for the first time. A RF-separated 22GeV/c K^+ beam and RICH technique for particle identification are used. The goal of CKM is to collect 100 signal events in the SM with 10 background events.

7 Blind analysis

A technique of "blind analysis" is widely used in the field of rare kaon-decay experiments. The principal idea is to hide the answer in order to avoid human bias. The procedure is as follows. At first, the signal region ("BOX") in multi-dimensional "cut" space [6] is pre-determined. Other cuts are chosen without looking at the events inside the BOX, and are frozen. Background

[6] Not only the kinematic variables in the final plot but also some important variables for timing, visible energy and so on can be used to define the signal region.

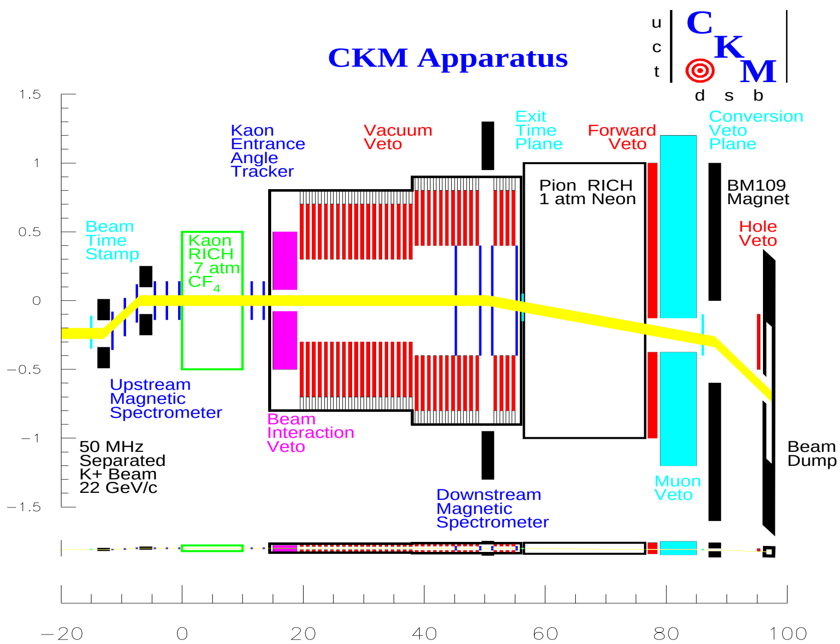

Figure 10: *Plan-view of the proposed CKM detector at FNAL. The lower section shows the true proportions of the apparatus.*

estimates in the regions "outside-the-BOX", where the background-to-signal ratio is expected to be higher than that in the signal region, are compared with the number of events observed in them, and in the final step the BOX was opened and the number of signal events is counted. With the same philosophy, in measuring a branching ratio, asymmetry, polarization and so on, some blind numbers are added or multiplied until looking at the result in the final step.

One of the main reasons to take blind analysis in rare decay searches is, we expect only a handful signal events, even if we succeed to detect, and we should be careful to avoid playing with them (adjust a cut to remove or save a candidate event, ...) in the analysis.

8 T-violating transverse muon polarization in $K^+ \to \pi^0 \mu^+ \nu$

Though the $K^+ \to \pi^0 \mu^+ \nu$ itself (branching ratio $= 3.18 \pm 0.18\%$ [14]) is not rare, here is a good example of looking beyond the SM by precisely measuring

a decay property with high statistics. The transverse muon polarization P_T of the $K^+ \to \pi^0 \mu^+ \nu$ decay (the perpendicular component of muon spin vector relative to the decay plane determined by the momentum vectors of muon and pion in the K^+ rest frame) is a T-odd quantity, and a nonzero value of P_T indicates violation of T invariance. Any spurious effect from final-state interactions is small, because no charged particle other than muon exists in the final state. P_T due to the CP violation in the SM is as small as 10^{-7} [35], while new sources of CP violation could appear in the polarization at the level of 10^{-3}.

The E246 collaboration [36] measures the charged track and photons from K^+ decays at rest with the superconducting toroidal spectrometer (consisting of 12 identical, 0.9-Tesla spectrometers arranged in rotational symmetry), which enables to control possible sources of the systematic error in polarization measurement. No transverse polarization $(-0.33 \pm 0.37_{stat} \pm 0.09_{syst})\%$ was observed by a preliminary result from the the E246 collaboration [37] with their 1996-1998 data set. Combined with the 1999-200 data set, which is being analyzed, the error in P_T is expected to be reduced to 0.003.

E246 reported the form factors of the $K^+ \to \pi^0 e^+ \nu$ decay [38]. The PDG's combined results [14] for the ratio of the strengths of scalar and tensor couplings to that of the vector coupling ($f_S/f_+(0)$ and $f_T/f_+(0)$, respectively) differ from zero and contradict the V-A interaction in the SM. After analyzing the observed Dalitz plots containing 41 K events from their special trigger runs in 1996-1997 with two sets of magnetic field (0.65 Tesla and 0.9 Tesla) in the spectrometer, $f_S/f_+(0) = -0.002 \pm 0.026_{stat} \pm 0.014_{syst}$ and $f_T/f_+(0) = -0.01 \pm 0.14_{stat} \pm 0.09_{syst}$ were determined. These values are consistent with the SM prediction of zero. E246 also reported the ratio of the $K^+ \to \pi^0 \mu^+ \nu$ and $K^+ \to \pi^0 e^+ \nu$ decay widths [39] $0.671 \pm 0.007_{stat} \pm 0.008_{syst}$.

9 Lepton flavor violation in kaon decays

Lepton flavor (LF) violation has been studied for more than 50 years, and is a current topic of particle physics because of recent results on neutrino oscillation and theoretical predictions to the processes induced by Supersymmetric loop effects. There are new proposals to search for the $\mu^+ \to e^+ \gamma$ decay at 10^{-14} in PSI [40] and the $\mu^- N \to e^- N$ conversion at 5×10^{-17} in BNL [41].

Experimental search for LF violation in kaon decays ($K_L^0 \to \mu^\pm e^\mp$, $K_L^0 \to$

$\pi^0\mu^\pm e^\mp$, $K^+ \to \pi^+\mu^+e^-$) [7] also has a long history. The experimental limit on neutrino masses and mixing more than 10 years ago, unfortunately, had already restricted the branching ratio of the $K_L \to \mu^\pm e^\mp$ decay, for example, to be less than 10^{-15} even with possible Left-Right asymmetry [42]. Introducing Supersymmetric models would not change the situation so much because "Super-GIM" suppression mechanism is expected for both quark and lepton sectors [43]. The advantage of kaon decays is to be able to investigate the LF violating process involving both quarks and leptons with the highest sensitivity. Assuming a number for quarks and leptons in the same generation (1 for down-quark and electron, 2 for strange-quark and muon, ...) due to Horizontal Symmetry or Compositeness or Leptoquarks, the net number is conserved in the LF-violating kaon decays. The mass of hypothetical generation-changing gauge boson for tree-level effects should be a few hundred TeV scale [44].

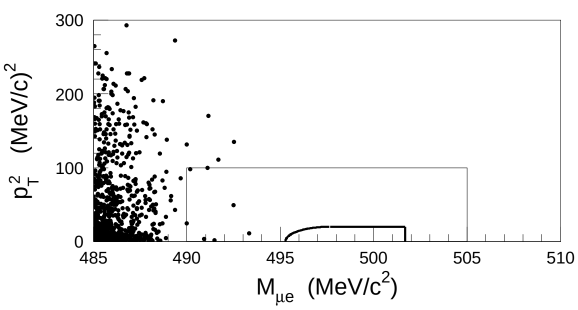

Figure 11: *E871 result on $K_L^0 \to \mu^\pm e^\mp$: plot of the two-body transverse momentum squared p_T^2 versus the two-body invariant mass $M_{\mu e}$. The exclusive region for the blind analysis is indicated by the box. The signal region is indicated by the smaller contour.*

The best upper limit on the branching ratio of the $K_L^0 \to \mu^\pm e^\mp$ decay $< 4.7 \times 10^{-12}$ [8] was set by the E871 collaboration [45] based on zero events in the signal region with the background estimate of 0.1 events (fig.11). An

[7] Both two-body and three-body decays have to be explored in spite of the phase-space difference, because the $K \to \pi\mu e$ decay is sensitive to a vector or scaler current.

[8] This is the most stringent upper limit to particle decays.

upper limit on the branching ratio of the $K_L^0 \to \pi^0 \mu^\pm e^\mp$ decay $< 4.4 \times 10^{-10}$ was set by a preliminary result from the KTEV collaboration [46] with their 1997 data set based on two events in the signal region with the background estimate of 0.61 ± 0.56 events. An upper limit on the branching ratio of the $K^+ \to \pi^+ \mu^+ e^-$ decay $< 2.8 \times 10^{-11}$ was set by the E865 collaboration [47] with their 1995-1996 data set (zero events in the signal region) and the result of an earlier experiment E777 [48]. Combined with the 1998 data set, which is being analyzed, the limit is expected to reach $\sim 1.5 \times 10^{-11}$.

E865 reported the upper limit on the branching ratio of the $K^+ \to \mu^+ \mu^+ \pi^-$ decay [49] $< 3.0 \times 10^{-9}$. This decay is a neutrino-less "double muon" decay changing total lepton number by two and provides a unique channel to search for effects of Majorana neutrinos in the second generation.

10 Summary

Table 2: *Progress in the field of kaon rare decays.*

decay modes		PDG-86	PDG-96	PIC-01
$K_L^0 \to \mu^+ \mu^-$	in 10^{-9}	9.1 ± 1.9	7.2 ± 0.5	7.18 ± 0.17
$K_L^0 \to \pi^0 e^+ e^-$	in 10^{-10}	< 23000	< 43	< 5.1
$K_S^0 \to \pi^0 e^+ e^-$	in 10^{-7}	-	< 11	< 1.4
$K^+ \to \pi^+ \nu \bar{\nu}$	in 10^{-10}	< 1400	< 24	$1.57^{+1.75}_{-0.82}$
$K_L^0 \to \pi^0 \nu \bar{\nu}$	in 10^{-7}	-	< 580	< 5.9
$K_L^0 \to \mu^\pm e^\mp$	in 10^{-12}	< 6000000	< 33	< 4.7
$K_L^0 \to \pi^0 \mu^\pm e^\mp$	in 10^{-10}	-	-	< 4.4
$K^+ \to \pi^+ \mu^+ e^-$	in 10^{-11}	< 500	< 21	< 2.8

Let us summarize the progress in the field of kaon rare decays in the last 15 years (tab.2). The experimental results reported in this article (PIC-01) are compared to the results on Review of Particle Properties in 1986 (PDG-86) [50], when I started particle physics as a graduate student, and in 1996 (PDG-96) [51], when the first round of rare decay experiments are completed. The improvements were enormous between 1986 and 1996, and about an order of magnitude of improvements are achieved in the last 5 years. We do expect further improvements and potential discoveries by the next round of experiments in the next five to ten years.

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